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### THE PHYSICAL PHENOMENA

OF

HARBOR ENTRANCES.

THEIR CAUSES AND REMEDIES.

DEFECTS OF PRESENT METHODS OF IMPROVEMENT.

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Every well-considered plan for improving the entrance to a harbor must take into account the existing physical conditions or features of the site, and the causes which have produced them. These features are composed of the land-drainage, the inner basin, the gorge, the outer basin, the bar and the ocean. In passing from the fresh to the salt water system, there may be one or more channels having some peculiar characteristics, which are not mere accidents, but the results of certain forces. Before any radical or permanent improvement can be effected it is necessary that the forces operating at any point

should be fully understood, and, so far as possible, be measured. In tracing step by step the causes from their effects, I have found the circle of investigation unavoidably widening, until it embraced many of the physical phenomena pertaining to the North Atlantic Ocean.

The initial point in this study is the form of the bed or mould of alluvial harbors, supposed to be of material sufficiently plastic to reveal the effect of the forces operating upon them. I have heretofore elsewhere called attention to the important deductions to be obtained from noting the position of



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the submerged crest line of bars, as well as from the relative slopes of sections along the thalweg of the channel or across the bar, as indicating the direction of movement of the sand and of the flexure of the outer ends of the channels, after passing the gorge, either up or down the coast. The immediate cause of this flexure was asserted to be a littoral component which rolled up the sand on the flood tide and compressed the ebb stream against one or other of the adjacent shores. But why this resultant should have been so constantly operating in opposite directions at different entrances was not then fully understood or stated.

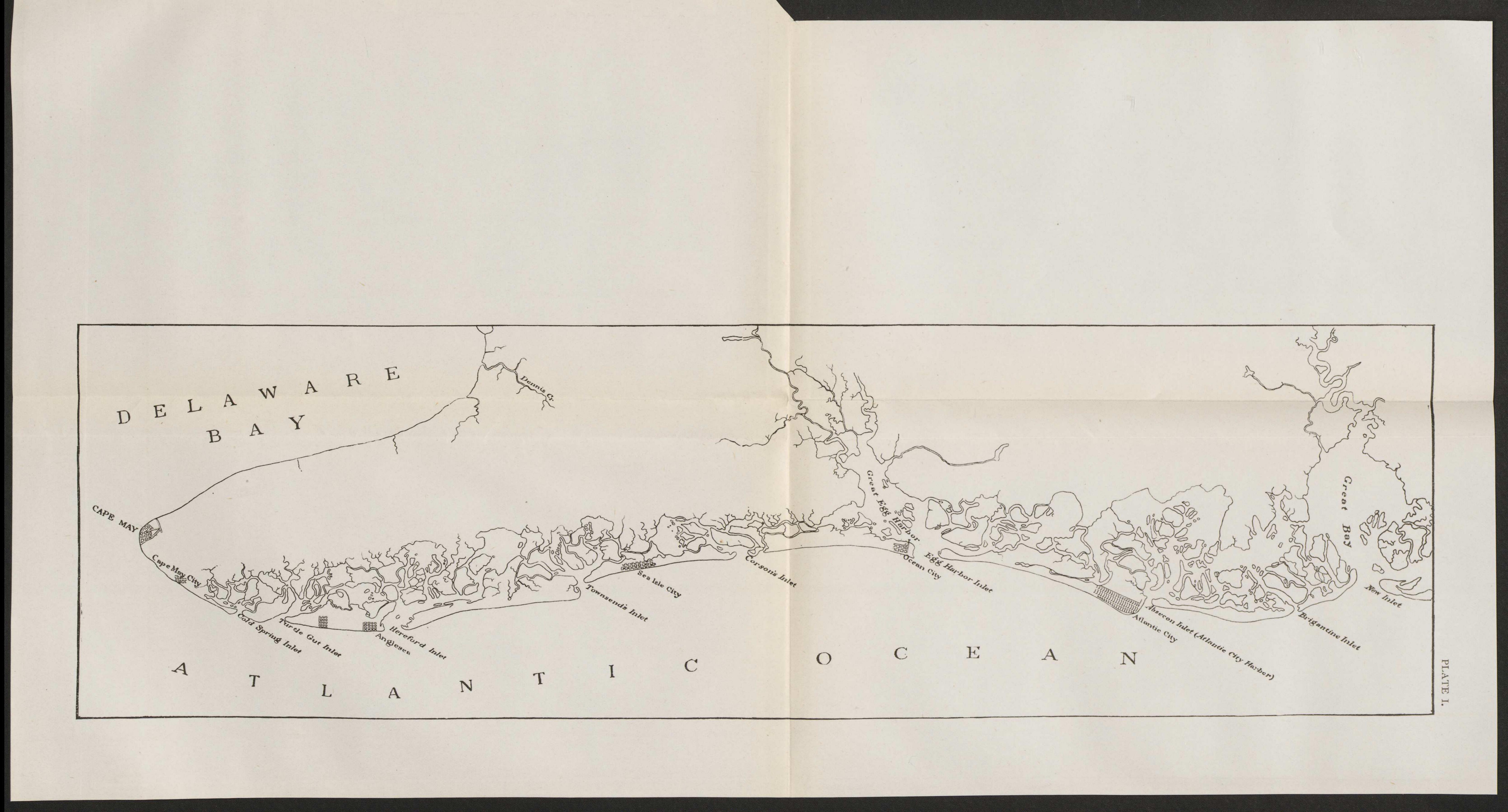
It is the object of this paper to collate certain observed facts, for the purpose of explaining these phenomena and of deducing therefrom a conclusion of practical value in the economical solution of the problem of improving our harbor entrances.

### TYPICAL FORMS. (See Plate I.)

In examining the plan of any entrance it is generally found that the ends of the islands forming the outlying cordon are elongated into spits or hooks, curving inward, with a smooth outer and a rugged inner shore line; that one of the points is sharp, and the other blunt or round headed; that the sharp

point usually recedes from the general coast line; that the seaward slope of a cross section of the bar is less steep than the inner slope, except where the ebb streams cross it; that the flood tide usually approaches the entrance at first in a direction more nearly parallel to the sharper lip and normal to the blunt one, rolling up the gentler slope and depositing sand on or within the crest of the bar, where "breakers" are found; that along the shore of the sharp point there is a shallow channel cut out by the flood, and curving around the blunt, projecting lip of the gorge there is the main deep-water chan-





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nel produced by the ebb. Between these limits are found one or more secondary or swash channels, which provide egress for the lateral overflow, so to speak, of the ebb and correspond to the waste weirs or crevasses of a stream.

### CHARLESTON HARBOR.

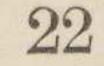
These characteristics are well illustrated in the harbor of

Charleston, S. C., as seen on the chart of 1858 (Fig. 1). I have selected this early date as it shows the current movements and condition of channels before extensive improvements were begun. Here the thalweg approaches the gorge in a direction nearly east and west, and on passing out it is deflected fully 90°, and extends nearly north and south. Hugging the northern spit is the flood channel, known as Maffit's or Sullivan's Island channel, with nine (9) feet on its crest at the *inner* end. Then appear the breakers of Drunken Dick shoal, followed by the weir channels known as the North channel, with ten (10) feet at its *outer* end; the swash channel, nine (9) feet; the main ship channel, eleven (11) feet, and Lawford's channel, ten (10) feet. The shortest distance to the outer eighteen (18) feet contour

from the gorge is three and one-fourth  $(3\frac{1}{4})$  statute miles, whilst by the main ship channel courses it is *seven* (7) miles, or more than double, so that vessels entering from the north must make a detour of nearly fourteen (14) miles to cross the bar.

At the only current station outside the bar the set of the flood during the first and second quarters (its most energetic period) is *parallel to the shore* of Sullivan's Island, or about west south-west, but it swings around through west to nearly north-west, or normal to the gorge during the last quarter. The stations inside of and on the bar show





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local modifications of the flood and a movement towards the entrance, due to the diminution of resistance in that direction, especially during the last quarters of the flood. The plane of maximum ebb scour, as indicated by the depth of water on the bar, is limited to about twelve (12) feet.

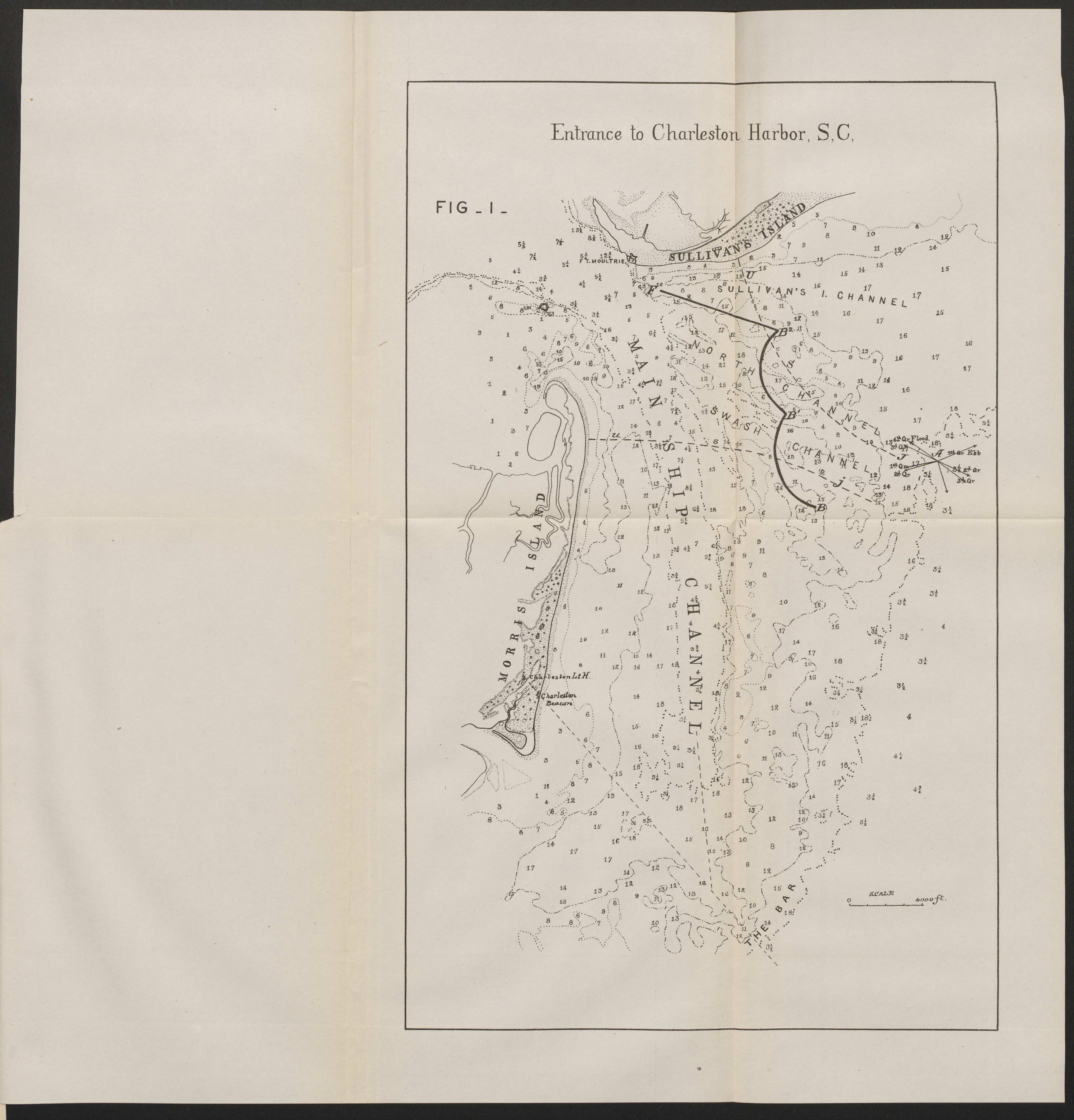
Similar features will be noticed at Galveston (Fig. 2) and at other entrances, but it does not always happen that the crossing of the bar is so far from the gorge, nor is it always to the south. The position of this important point is the resultant of the internal and external forces which affect the movement of the main ebb stream.

### THE FORCES.

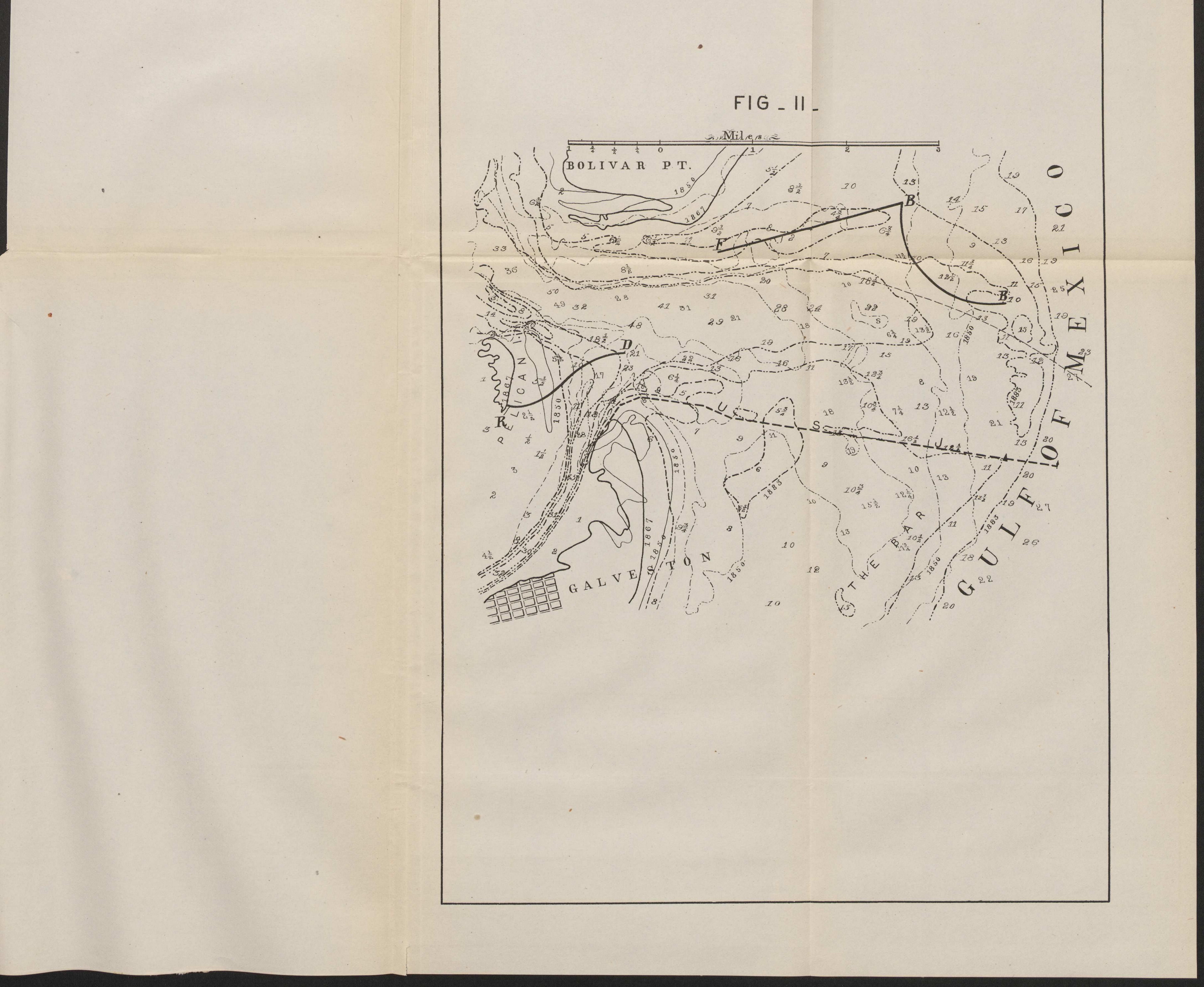
The *internal* forces are those resulting from the form and extent of the inner basin, the volume of the tidal prism and the relative directions of the tidal and river currents as they approach the gorge. The *external* effects are those resulting from the form, position and extent of the banks which have been piled up by the flood and obstruct the ebb. Hence it follows, if the flood pressure and movement is from the south side of the entrance the channel will be to the north, as the banks will be more extensive on the former side, offering greater resistance and deflecting the ebb stream and crowding it in until it is supported on its opposite flank by the shore. If the flood resultant comes in from the northern side, the reverse is true.

Again, if the confluent ebb streams of the inner basin are so directed by natural or artificial constructions as to commingle and unite their energies, instead of opposing one another, as most frequently occurs, the momentum of the united stream will be greater and the crossing on the bar be consequently deepened. This will be better understood by observing that the inner





# Entrance to Galveston Harbor, Texas,



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basin is generally composed of three subdivisions, viz: One extending along the islands on either hand, and one stretching to the rear. At the ebb of the tide the prisms of discharge are all approaching the gorge at the same time. In consequence. of the inward flexure of the spit at this place, one or both of the lateral currents are reflected into the face of the main discharge, and thus diminish its energy, which it is the object

of the engineer to conserve.

These general effects can be seen by a comparison of the position and depth of the bar crossings along the coast line of the Middle and Southern States. One of the most striking and typical instances of the effect of the internal concentration and conservation of energy is that of the *Port Royal* entrance, where there is a depth of twenty-one (21) feet on the bar, due to the increased intensity of the resultant ebb, produced by the confluence of the Beaufort, Broad and Chechessee rivers, whose thalwegs approach in directions nearly parallel. Here, too, is observed the flexure of the outer stream to the southward, showing clearly the existence of an excess of flood action from the northward, and the piling up of sand banks on this side to be eroded by the ebb.

The opposite effect resulting from conflicting internal cur-

rents is il'ustrated in the case of the Galveston entrance (Fig. 2).

An examination of the various entrances leaves no doubt of the existence of such a littoral flood movement, whereby the sands of the beaches are transported to and deposited in front of the inlets, where the racing waves, no longer resisted by and reflected from the shore, escape through the break in the barrier which forms the outlying sandy cordon defending the coast.



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### OCEAN DYNAMICS.

The effect of this racing of the waves in search of an escape from the pressure of the flood tide is to scour off and prolong the sharper lip at the gorge and to flatten out and beat back the opposite shore, thus shifting the position of the "inlet" until in some instances it is transported considerably to one side of the medial line of the inner bay, or entirely closed.

Thus, the position of the thalweg is made to cross the gorge obliquely, and furnishes additional evidence of the resultant direction of the external or flood movement. \*These movements are fully illustrated in the comparative chart herewith submitted of Barnegat Inlet (Plate IV), from which it is seen that the flood resultant comes in from the north, prolonging and eroding the northern spit compressing the ebb against the lighthouse shore, from which it has cut away so great a volume as to seriously endanger the structure. The total movement in about thirty-four (34) years has been half a mile, or about eighty (80) feet per year. Had this action been previously recognized the lighthouse would probably not have been placed in so dangerous a position, but on the north spit. During the prevailing north-east winds of this spring the encroachments have been more rapid and extensive than at any previous time. The remedy is apparent, but will be stated generally further on in this communication. The effort of the ebb is not to oppose the flood resultant directly, but to turn away therefrom and assume a direction as nearly as may be at right angles thereto.

Thus the flood will roll the sand up the gentler outer slope to the crest in a direction normal to the main channel, while the ebb will sweep across its path on the line of least resistance,

\*This paragraph was interpolated here after the paper was written. See Supplement.



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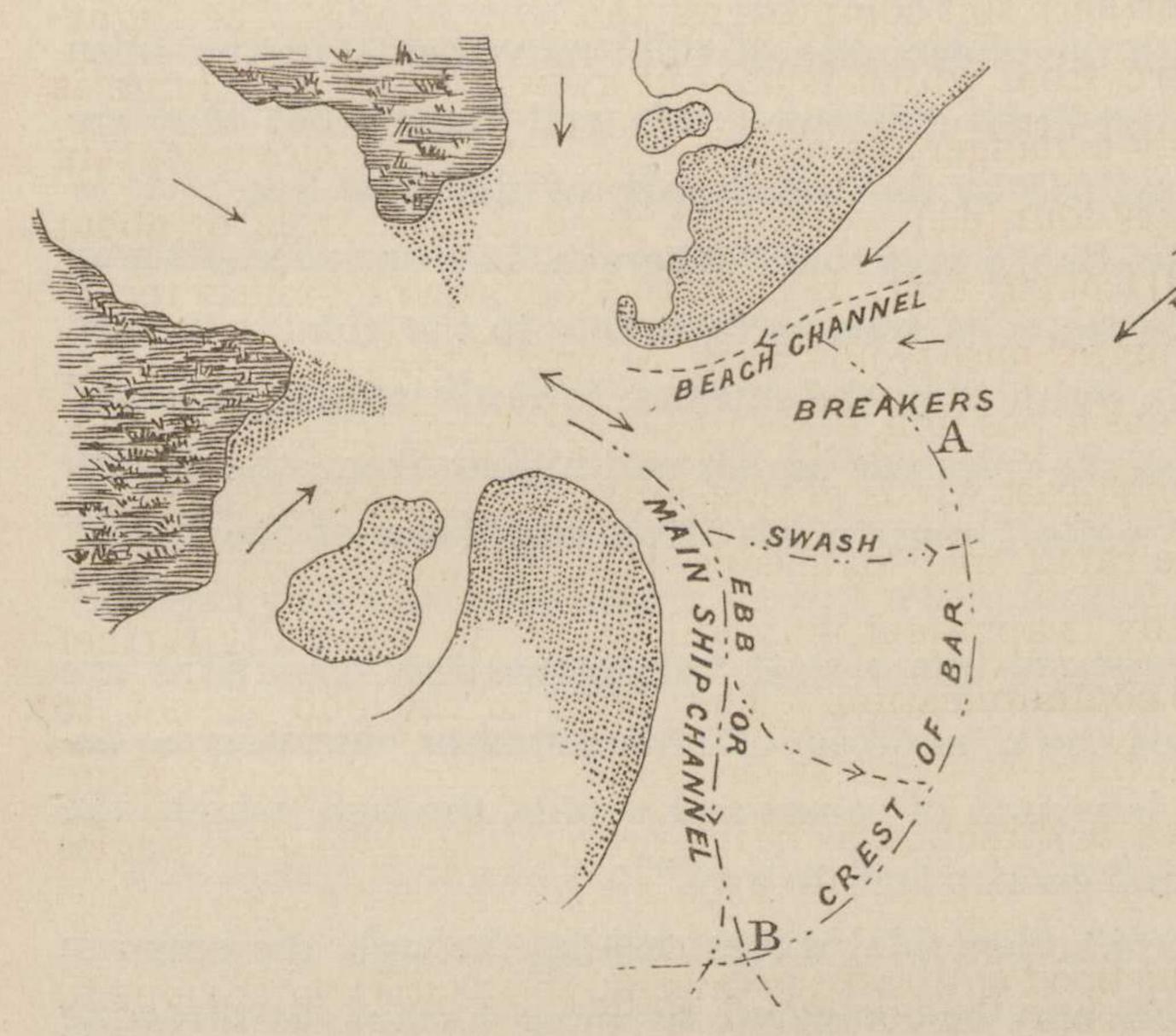
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which lies behind and parallel to the barricade formed by the flood, and effect *its maximum result at the point of minimum resistance*, which is that point of the bar farthest removed from the direct action of the flood. This enceinte formed by the flood is also the cause of the beach channel lying under the near spit, since a portion of the flood is deflected by the bar into the re-entrant between it and the shore, whilst another

portion is rolled along the beach, and these two components unite in a resultant cutting across the inner angle of the bar and carrying silt into the gorge.

The action of these forces may possibly be made clearer by reference to a simple diagram:

- A. Point of maximum flood force.
- B. Point of minimum flood resistance.



THE TIDAL MOVEMENTS PRODUCING THESE PHENOMENA. Thus far I have been considering the local features, and deducing therefrom the *general condition* of the hydrodynamic PROC. AMER. PHILOS. SOC. XXV. 127. D. PRINTED FEB. 20, 1887.



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forces which have produced the observed effects. It now remains to determine why this resultant should be sometimes from the north-east and at other times from the south-east. This leads at once to an examination of the phenomena attending the approach of the tidal wave and the position of the cotidal lines with reference to the coast line. For this purpose there are available the general cotidal maps of Prof. Guyot, and the more detailed maps of Prof. Bache, accompanied by the tide tables of the Atlantic coast, as contained in the United States Coast Survey Reports. Meagre as these data are, they are yet sufficiently abundant to confirm the existence of the alleged resultant movements, and to verify in the most satisfactory manner the reliability of this method of determining the forces by their effects.

Although the phenomena of tidal movements in the open ocean are but little understood, it is well known that they are sensibly modified by the topography of the coast line.

Professor Bache says that "where a bay or indentation of the coast presents its opening favorably to the tidal wave and decreases in width from the entrance towards its head, it is well known that the tides rise higher and higher from the mouth upwards," while Lentz, in his "Ebb and Flow of the Tides,"

says:

"The intricate, theoretical, tide-generating conditions are complicated by a number of circumstances, forming a bewildering labyrinth of causes and results, through which the human mind cannot find its way."

"The numberless tidal waves rushing through the ocean in all directions may be compared to those formed by throwing ten (10) or twenty (20) stones into a small pond. By watching these we may learn as much as we know about the tidal waves moving on our ocean," and he adds, "this certainly is discour-



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aging, and we only know that we do not know anything." While this conclusion may be true as to the currents in the open sea, it cannot be applied to those along shore, for an examination of our coast line reveals some striking and definite features. These are, the existence of four (4) prominent salients upon which the tidal crest impinges, and by which it is broken up into components, which are deflected into the bays on either side. At the points of incidence there will generally be found large inner sounds, extensive shoals and bars, and the heavy precipitation resulting from the checking of the momentum of the wave, the change in its direction and the interference and eddies produced thereby. Then follows the comparatively smooth reach of straight beach, along which the component tidal waves travel inland from the chord joining the salient capes, and finally, the indented and serrated shore where the opposing components in the same sinus meet at the point farthest from the chord, and where the tides are highest, the marshes most extensive, and the outlying cordon of sand is replaced by numerous islands and intricate " back " channels. Here the tidal wave is brought to rest, and exerts its energy in a direction nearly normal to the coast, whilst along the flanks of the bay it is moving obliquely to the shore, but always towards the bight, except when locally disturbed, and with a dynamic energy, begotten in mid-ocean, which compresses the sand upon the shores and transports it in the direction of that motion.

The motor in the case of the flood tide is chiefly universal gravitation, which raises the crest of the flood wave from two (2) to five (5) feet, and rolls it forward upon our eastern coast line until its acquired momentum is met, modified and ultimately destroyed by the inertia of the mass of sand which it encounters.



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So far as the ebb is concerned, it merely rolls off from the fore-shore, chiefly under the influence of terrestrial gravitation, and having its initial velocity at high-water line, its transporting energy is feeble, and it, therefore, exerts no material influence in modifying the exterior lines of the coast.

THE SOUTHERN BAY.

These generalities are more clearly exemplified and confirmed by the facts exhibited on the accompanying chart (Plate III). Beginning at Cape Florida, the heights of the tides at the various external stations are marked in feet, whilst the cotidal lines are plotted as enlarged from the United States Survey Report of 1854.

By following the coast northwardly from Cape Florida, it will be found that the height of the tide increases from 1.5 to about 7.4 feet at Jekyl Island, between St. Simon and St. Andrew's Sounds, which is the most remote point, about two hundred (200) miles, from the chord of the arc; also, that the outer ends of the main or ebb channels are flexed northwardly, and that even the land drainage extends in the same general direction. As the bight of the bay is approached, the land discharge becomes more nearly nor. mal to the coast and the shore line more deeply indented, and after passing this point, the tidal elevations decrease (with one exception), the directions of the land and channel discharges are reversed and the shore lines become smoother. This reach of coast is characterized by three secondary bays, separated by the groins of Cape Lookout and Cape Fear. These capes are the resultants of the opposition of the tidal wave to the fresh water discharge, which being unable to effect its escape in the face of the flood is turned to the west and south by the pressure of the



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tidal component deflected from Cape Hatteras. An inspection of any general map of North Carolina reveals the fact that instead of the rivers being normal to the coast, they are turned for considerable distances back from their mouths into a direction nearly parallel with the shore line, and effect their discharge under the lee of the Cape, thus conforming to the general law of least resistance.

The capes and bars thus formed by the parallel and confluent fresh and salt water currents deflect the littoral component until it is met by the direct flood crest and returned to the beach near the middle point of each of the three (3) bays, Raleigh's, Onslow's and Long's. Here it is resolved into secondary littoral currents along the ellipses thus formed. The eastwardly components of these waves compress the *ebb channels against the eastern shores* of the outlets, as at Beaufort, N. C., while those to the westward, reinforced by the original wave, race along the beach, closing or shoaling the inlets and forming with the land drainage the long spits above described.

The time of high water is also much earlier outside or to the eastward of the cape than it is within, in consequence of the circuitous route required to be taken by the flood. The suction thus produced causes a draft current to the eastward, which deflects the ebb discharge from the inlets in this latter direction and increases the height of the tides inside the capes.

It is also a notable fact that a straight line drawn from Cape Roman to Hatteras is just tangent to Capes Lookout and Fear, and that the transverse and semi-conjugate axes of the ellipses of Long and Onslow Bays are respectively equal, while Raleigh Bay is somewhat smaller in both directions and has a steeper scarp than either of the others (due to the incident wave). The shore to the north of Cape Hatteras is deflected from the chord of the three bays produced at an angle of 45° for a dis-



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tance of twenty-six (26) miles, when it again bends to the westward through an angle of 30°, and continues in an unbroken stretch of ninety-four (94) miles to Cape Henry. The only outlets on the eastern cordon of Hatteras are near the point of deflection where the northward component from the cape and the normal wave commingle.

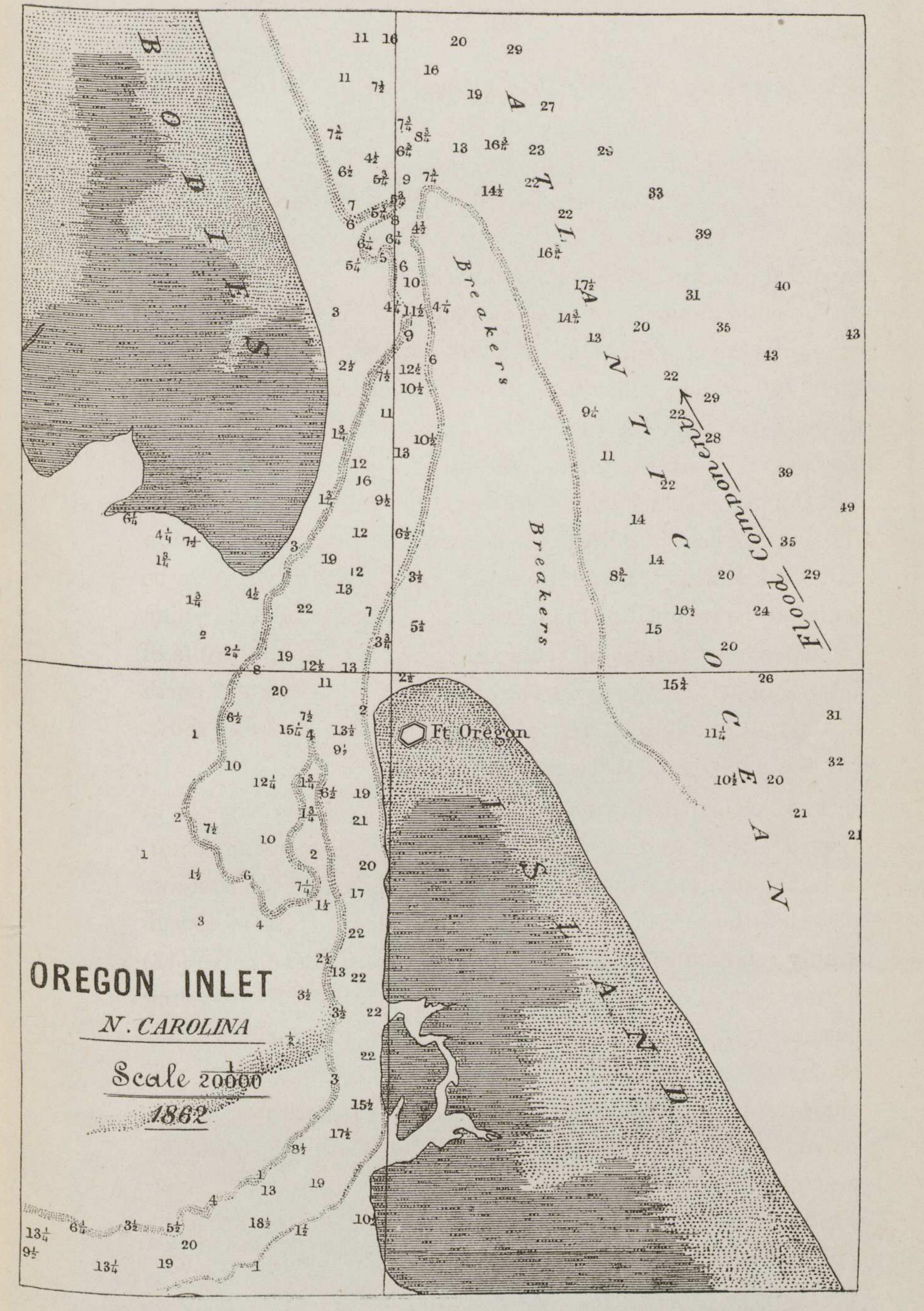
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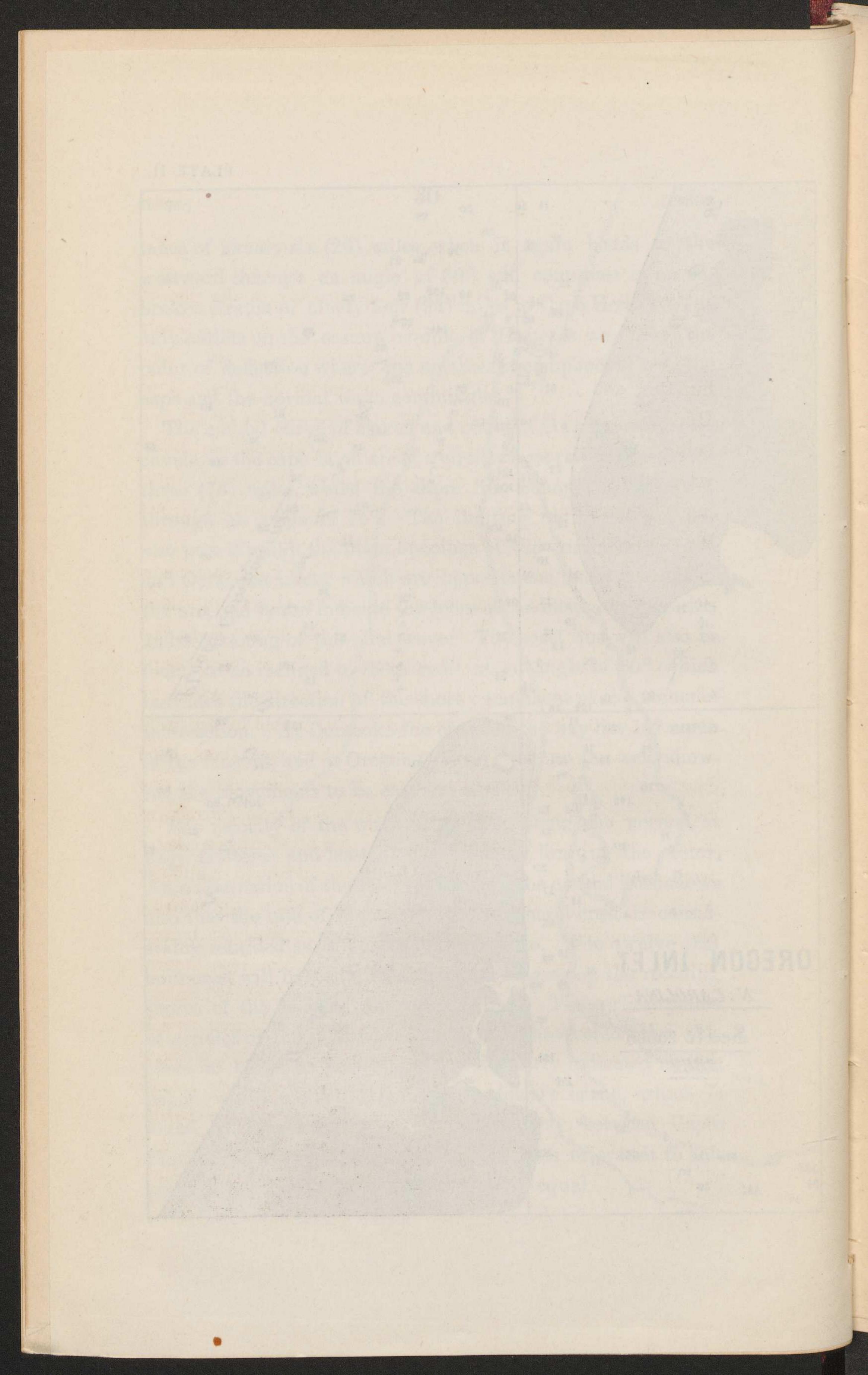
The cotidal curve of eleven and one-half  $(11\frac{1}{2})$  hour interval envelopes the cape in an arc of a circle whose radius is seventythree (73) miles, whilst the shore line changes its direction through an angle of 74°. The limiting radii of this sector also pass through the main openings of the cordon at Oregon and Ocracoke Inlets, which are opposite the tangent points of the arc, and hence indicate the locus of the change of direction and weakening of the tidal wave. The coast line will also be found to be inclined to these radii at an angle of 80° which indicates the direction of the shore component at the points of intersection. At Ocracoke the chord of the bay lies 10° north of the tangent, and at Oregon (Plate II) 10° to the west, showing the movements to be east and north.

The velocity of the wave is greatest along the normal at Cape Hatteras and least along the radii limiting the sector. An examination of the interval between the cotidal lines shows also that the rate of movement of the general crest is considerably retarded as it approaches the shore. The twelve (12) hour crest will be seen with its flanks rolling along the receding shores of the bays, as already described. The earliest points of contact of the tidal wave are readily discovered from this chart to be at or near the points formerly indicated in this paper, whilst the latest point is at Jekyl's island, which is found by measurement to be just midway between Capes Florida and Hatteras, thus making the times of transit to this point of meeting of the flood components, equal.



### PLATE II.





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### THE MIDDLE BAY

Extends from Cape Hatteras to Nantucket, a distance of about five hundred and forty (540) miles. Its longest ordinate is that opposite the New York entrance, where it is one hundred and forty (140) miles. The shore line from Cape Henry to Sandy Hook being nearly parallel to the chord and being broken by the two large bays of Chesapeake and Delaware, there is not so great a compression of the two converging tidal components as was observed in the southern bay, yet the same general characteristics are observable. Proceeding north from Hatteras, there is the long sandy cordon, with its smooth beach stretching in an almost unbroken curve to Cape Henry at the mouth of the bay. Here the flood wave is interrupted and deflected by the opposing Cape Charles, the outer shore line of which is deeply scored by sounds and studded with islands and shoals, created by the flood which cushions upon it. The northern component from Cape Hatteras practically terminates here and is dissipated by the bay and the islands of the outer coast as far up as Paramores Bank. In a similar manner the component rolling westerly from Nantucket, is absorbed by Long Island Sound and New York and Raritan Bays. The normal flood wave approaching the coast on either flank of Delaware Bay is resolved by the most salient points of New Jersey and Virginia into littoral components one of which travels from a point north of Barnegat, northward to Long Island. It is this component which has created and maintained Sandy Hook and which is eroding the beach at Long Branch. (The westwardly, or Long Island component has made the spit at Coney Island, and the resultant of both, maintains the flood channel under this point.) The other or New Jersey component moves towards Cape May

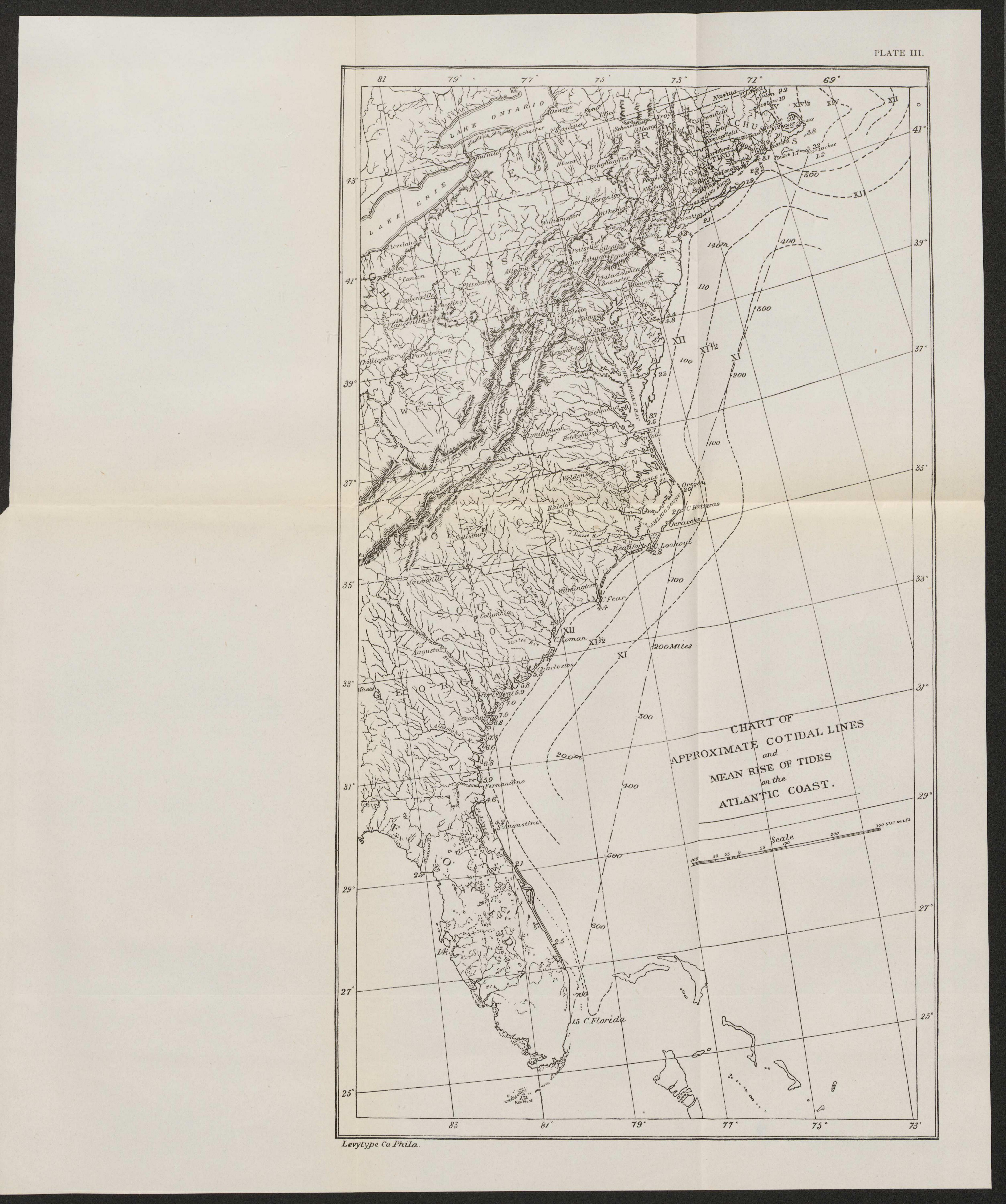


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and builds the bars in front of Barnegat, Absecon and other inlets, crowding the channels over against the southern shores of these inlets, which are thus eroded by the ebb currents. The same physical features will be found to result from the components acting north and south from a point near Green Run Inlet, Md., on the coast between Cape Charles and Henlopen. The tidal observations in this bay are indicated on the map (Plate III) and confirm this theory. The mean rise of the tide at Cape Charles is only 2.5 feet, because of the relief afforded by the bay. At Cold Spring Inlet it is 4.4, and at New York entrance 4.8. Here it attains its maximum height and thence diminishes eastwardly to Nantucket. From the secondary point of reversion near Barnegat on the New Jersey coast, the littoral currents are indicated by the heights of the tides. Thus at Barnegat they are 2 feet, at Absecon 3.9, at Cold Spring 4.4, etc. The interference of the tidal waves and the great difference of three (3) hours in the time of high water which is compressed in the short space between Martha's Vineyard and Monomoy, is too extended a subject to be included in this paper, which is intended merely for the alluvial coast line south of Long Island. Its consideration is therefore omitted, but the mean tides are recorded in part of the northern bay to illustrate the continuance of the concentration of the tidal energy and progression as previously observed. These same laws and phenomena are found to exist on the Pacific Coast and will explain many of the effects which have only been casually noted by mariners. The phenomena are identical with those already described. The laws are of general application.





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THE JETTY SYSTEM AS AT PRESENT APPLIED.

In applying tidal scour to the improvement of harbor entrances in the United States, these three (3) principles have been laid down as fundamental:

1. The works should be so designed that "they should not im-"pede the inflow to such an extent as to prevent the tidal

"basin being filled at every influx of the tidal wave."

- 2. "They should control the outflow to such a degree and in "such a manner that a channel of the required depth will "be maintained through the bar."
- 3. "They should not to any considerable extent, cause a move-"ment seaward of the main body of the bar; that is, the "general position of the bar should be independent of the "effects produced between and beyond the heads of the "jetties."

The attempt to reconcile these conflicting conditions as to concentration of ebb and free admission of flood resulted, after mature consideration, in a plan involving low or submerged jetties, which were tried as an experiment both at Charleston and Galveston. The result has been to push the body of the bar seaward, without at the same time materially deepening the water on its crest. The cost of these experiments has reached nearly \$3,000,000. These plans are defective, not only in their failure to depress the plane of tidal scour over the bar, but they are so designed as to divert the ebb stream directly into the face of the flood, where the resistance to be overcome is the greatest. The plans for Galveston have been modified, and it is now proposed to raise the jetties to high water, at an estimated cost at this port alone of \$7,000,000. But even if this be done upon the two PROC. AMER. PHILOS. SOC. XXV. 127. E. PRINTED FEB. 21, 1888.



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lines as proposed, there will still be the serious violation of the first of the above established principles, and the further serious objection of directing this diminished tidal prism into the face of the flood, near its point of maximum energy, with nothing to lower the plane of tidal scour except the small amount of head due to contraction. This is in violation of the accepted rule that all works designed for river or harbor improvements should aid, rather than oppose, nature. To turn an ebb stream out of its natural bed and deflect it by jetties across a bar is to impose additional resistance; first, from the change of direction, and second, from the additional resistance opposed by the higher crest and steeper slope of the bar. There is also a less effective relative area of ingress due to the form of the converging jetties.

Unless there is a large augmentation of the tidal prism by land drainage or from some other source during the epoch of the flood, such works will not, in general, prove beneficial. The location of the mouth of the jetties and the general design of the works is evidence that the principles enunciated in this paper as to the action of the flood and ebb forces have not been, as yet, fully appreciated in the planning of works of this description. The South Pass jetties are subjected to totally different conditions, as the flood tide furnishes but a very small percentage of the ebb discharge.

# GENERAL REQUIREMENTS FOR HARBOR IMPROVEMENTS.

From what has already been presented as to the origin of the bars and the relations that exist between the flood and ebb resultants, it must be evident that the engineer who proposes to aid nature must so design his *external* works as to *prevent the flood tide from carrying sand into the channel* to obstruct



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the ebb and require more work of it for its removal. He should also see that the ebb be not diverted from its course, but be protected and defended by a line of detached breakwaters. This will further have the effect of confining the ebb waters, which would otherwise escape in the swash or weir channels, to the main stream, and so concentrate their energy upon a single point of the bar, and that point the one where the bar-building

forces are the weakest.

This barricade should not in general be joined to the beach at the shore end, but there should be left a wide opening across that portion of the bar which corresponds to the flood or beach channel. This should be deepened by the concentration of the flood currents, and the sand carried through the gorge would make fast land inside of the spit. Its quantity could be regulated by the extent of the opening. Thus the tendency of the flood to build its own barrier upon which to break would be aided, and the ebb would be protected in its escape. It also appears that but one such line of breakwater would in general be required, and hence the cost would be materially reduced. As it would occupy a site already dangerous to vessels, it would not increase the risks to navigation, but on the contrary, as it would project above the surface, it would be a

beacon as well as a breakwater, and would greatly diminish the difficulties of effecting an entrance by sailing vessels over the case of a double line of extended jetties with a narrow pass between them, especially if submerged.

### INTERNAL PROJECTS.

In connection with these external works there will be required in certain harbors regulating deflectors, or reaction dikes, to prevent the current interferences which produce hummocks, mounds, and even islands just inside the entrances

